

ERICA

EXPERIMENT ON RAPIDLY INTENSIFYING CYCLONES OVER THE ATLANTIC

FINAL REPORT

AD-A231 377

To the Office Of Naval Research
Marine Meteorology, Code 1122MM
on Contract N00014-85-C-0518



Statement "A" per telecon Dr. Robert
Abbey. ONR/Code 1122 MM

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December 1990

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Background

The Office of Naval Research (ONR) and the Contractor, Battelle Memorial Institute (Battelle), in July 1985 agreed to the following description, specifications, and work statement in contract N00014-85-C-0518.

1. The work and services to be performed hereunder shall be in accordance with those instructions contained in Exhibit A [deliverables] and the following paragraph.
2. The Contractor shall participate in the heavy weather at sea research program which shall include substantial interface for scientific logistics for projects GALE (Genesis of Atlantic Lows Experiment) and RICE (Rapid Intensification of Cyclones Experiment) which shall include the following tasks:
 - a. Provide project management and coordinate direction for the Rapid Intensification of Cyclones Experiment currently being planned for deployment in FY 89;
 - b. Provide for field direction of the RICE experiment;
 - c. Provide the Experimental Design Document detailing the interfaces, logistics, scientific objectives, and timetable for the successful conduct of RICE;
 - d. Provide the Summary Research Document detailing the actual conduct of the RICE project [this report];
 - e. Provide support as needed for the NSF/ONR supported Genesis of Atlantic Lows Experiment being conducted in the winter of 1986.

The project was renamed by Dr. R. K. Hadlock of Battelle, with ONR approval, in late 1985. Wherever the acronym RICE appears, substitute ERICA (Experiment on Rapidly Intensifying Cyclones over the Atlantic).

The contract further specified, per level of effort:

It is anticipated that in the performance of this effort, the Contractor shall be primarily responsible for the conduct of the work described herein. Such work will be under the general cognizance of Dr. Ronald K. Hadlock

The actual period of performance of this contractual effort extends from 31 July 1985 through 31 January 1991. This report to the cognizant ONR Scientific Officer, Dr. R.F. Abbey, Jr., represents the final deliverable on the Contract.

Synopsis

Dr. R. K. Hadlock's level of effort as Principal Investigator (sole investigator) was full time from August 1985 through January 1991, as specified by Contract N00014-85-C-0518 and its modifications. The following lists and discussion indicate the scope and completion of tasks performed by Dr. Hadlock under the contract. The scope and tasks are primarily concerned with project management.

1. Contract-specified tasks

a. Participation in GALE

Dr. Hadlock served as project GALE Status Coordinator 15 January to 15 February 1986 at the GALE Field Headquarters, Raleigh, North Carolina. He also performed with similar responsibility in CASP (Canadian Atlantic Storms Project), 16 February to 15 March 1986. GALE and CASP were concurrent and complementary 2-month field projects during the period 15 January to 15 March 1986: Dr. Hadlock acted as liaison between the two field projects.

b. Field direction of ERICA

Dr. Hadlock was responsible for planning, establishing, and predocumenting the ERICA field phase from August 1985 through 30 November 1988. This included a pre-ERICA field test in January 1988, based at the Naval Air Station, Brunswick, Maine (aircraft operations), and the World Weather Building, Camp Springs, Maryland (forecasting and Field Director's Office).

Dr. Hadlock served as ERICA Field Director from 1 December 1988 through 26 February 1989, based at the World Weather Building, Camp Springs, Maryland. Aircraft operations were directed from the Naval Air Station, Brunswick, Maine. The ERICA field phase was conducted in coordination with a Canadian ERICA effort based at and near Halifax, Nova Scotia.

Dr. Hadlock provided reporting on ERICA field phase accomplishment from 27 February 1989 through 31 January 1991.

2. ERICA Field Director Office's planning, review, and technical meetings (asterisks indicate formal ERICA presentations by Dr. R. K. Hadlock)

a. Prior to contract initiation

Fifth Conference on Cyclones, Port Deposit, Maryland, and ONR, Arlington, Virginia - April 1985

GALE Planning Meeting, and ERICA Steering Committee meeting
Raleigh, North Carolina - May 1985

- b. During ERICA contract funding
 - AGU/AMS IAMAP/IAPSO Assembly, Honolulu, Hawaii - August 1985
 - Workshop on Forecasting of Meteorological "Bombs," Seattle, Washington - September 1985*
 - CASP Planning Workshop, Halifax, Nova Scotia, Canada - November 1985*
 - GALE Planning Workshop, Raleigh, North Carolina - November 1985
 - ERICA general planning, ONR, Arlington, Virginia - May 1986
 - ERICA Definition Workshop, Drexel University, Philadelphia, Pennsylvania - September 1986*
 - ERICA operations: ONR, Arlington, Virginia - November 1986
 - ERICA aircraft operations, NOAA/OAO, Miami, Florida - November 1986
 - Airborne Science Workshop, Miami, Florida - February 1987
 - GALE and Extratropical Cyclone Workshops, and ERICA Steering Committee Meeting, Monterey, California - February 1987*
 - ERICA general planning, ONR, Arlington, Virginia - April 1987
 - ERICA general planning, ONR, Arlington, Virginia - June 1987
 - CMOS Congress, St. John's, Newfoundland, Canada; and ONR, Arlington, Virginia - June 1987*
 - ERICA general planning, Drexel University, Philadelphia, Pennsylvania - July 1987
 - ERICA Field Implementation Plan Workshop, Battelle Ocean Sciences, Duxbury, Massachusetts - September 1987*
 - Ocean Storms site visit, PMEL, Seattle, Washington - October 1987
 - GALE/CASP Workshop, Virginia Beach, Virginia - November 1987
 - ERICA buoy and NWSOP planning meetings, Bay St. Louis and Keesler AFB, Mississippi - December 1987**
 - Pre-ERICA field test, technical meetings, World Weather Building, Camp Springs, Maryland - January 1988
 - ERICA Aircraft Operations Workshop, Drexel University, Philadelphia, Pennsylvania - March 1988
 - ERICA Field Operations Plan Workshop, Monterey, California - March 1988*
 - ERICA technical site visits: NMC, Camp Springs, Maryland; Drexel University, Philadelphia, Pennsylvania; and Woods Hole Oceanographic Institution, Woods Hole, Massachusetts - May 1988

ERICA technical site visits: NAS Brunswick, Maine; Maritimes Weather Centre, Bedford, Nova Scotia; and Drexel University, Philadelphia, Pennsylvania - August 1988

ERICA technical site visits: NMC, Camp Springs, Maryland; and NOAA Winter Weather Workshop, Raleigh, North Carolina - September 1988*

GALE/CASP Workshop and ERICA Planning Meeting, Val-Morin, Quebec, Canada - September 1988*

Extratropical Cyclone Workshop and ERICA final field planning meeting, Drexel University, Philadelphia, Pennsylvania - October 1988*

ERICA field phase technical and review meetings, World Weather Building, Camp Springs, Maryland, and NAS Brunswick, Brunswick, Maine - December 1988 through February 1989

ERICA Field Phase Summary work session, Drexel University, Philadelphia, Pennsylvania - April 1989

ERICA Field Data Workshop, Drexel University, Philadelphia, Pennsylvania - May 1989

ERICA pressure data work session, Drexel University, Philadelphia, Pennsylvania - August 1989

ERICA Post-Field Phase Get-Together (workshop), University of Illinois, Champaign, Illinois - October 1989*

ERICA pressure data work session - Drexel University, Philadelphia, Pennsylvania - December 1989

ERICA pressure data work session, Anaheim, California - February 1990

ERICA pressure data work session, Boulder, Colorado - June 1990

ERICA pressure data work session, Drexel University, Philadelphia, Pennsylvania - September 1990

3. ERICA documentation produced within Office of Naval Research Contract N00014-85-C-0518. Asterisks indicate two reformatted documents that are reproduced in this report and that exhibit, in detail, project planning and accomplishments through the ERICA field phase. The papers directly follow this brief synopsis section.

Hadlock, R., Editor and contributor (1986), *ERICA Workshop Proceedings*, Drexel University, Philadelphia. 52 pp.

Abbey, R. F., Jr., C.W. Kreitzberg, and R. Hadlock (1987), *ERICA Overview Document*. 42 pp.

Hadlock, R., editor and contributor (1987), *ERICA Field Implementation Plan*. 118 pp.

Hadlock, R., editor and contributor (1988), *ERICA Field Operations Plan*. 398 pp.

- * Hadlock, R., and C. W. Kreitzberg (1988), The Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) Field Study: Objectives and Plans. *Bul. Am. Met. Soc.* **69**: 1309-1320

Hartnett, E., G. Forbes, and R. Hadlock (1989), *ERICA Field Phase Summary*. 469 pp.

- * Hadlock, R., and C. W. Kreitzberg (1991), Overview of the ERICA Field Phase. In preprint volume - *First International Winter Storm Symposium*, American Meteorological Society, New Orleans, January 1991

Forbes, G., C. W. Kreitzberg, and R. Hadlock (1990) The Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) Field Study: Synopsis and Impressions. To be submitted to *Bul. Am. Met. Soc.* January 1991.

4. Ocean-surface pressure data analyses

Since the end of the field phase, Dr. Hadlock has been occupied primarily with two tasks:

- a. Reporting operational data-acquisition results of the field phase,
- b. Performing analyses of the ocean-surface atmospheric pressure data, during Intensive and Limited Observation Periods (IOPs and LOPs), to objectively produce quality-controlled sets of the ship, C-MAN (Coastal-Marine Automated Network), moored buoy, and ERICA drifting buoy pressure data. Ship reports, in particular, must be examined in detail for inaccurate and/or nonrepresentative data.

Task b has required the major effort since the end of the field phase. The result is that the pressure data have been objectively rationalized for 6-h intervals during ERICA's IOPs and LOPs. Rationalization of these data, i.e., ensuring self-consistency among all the data, required the occasional declaration of invalid individual data reports, and the

determination of occasional biases in station pressure reporting. The objective process uses statistical techniques of optimal interpolation and univariate analysis. The techniques were developed for ERICA largely from a module of Drexel University's (C.W. Kreitzberg and D. Perkey) LAMPS model, configured to run on an ERICA-program Macintosh™ computer system and are further discussed below.

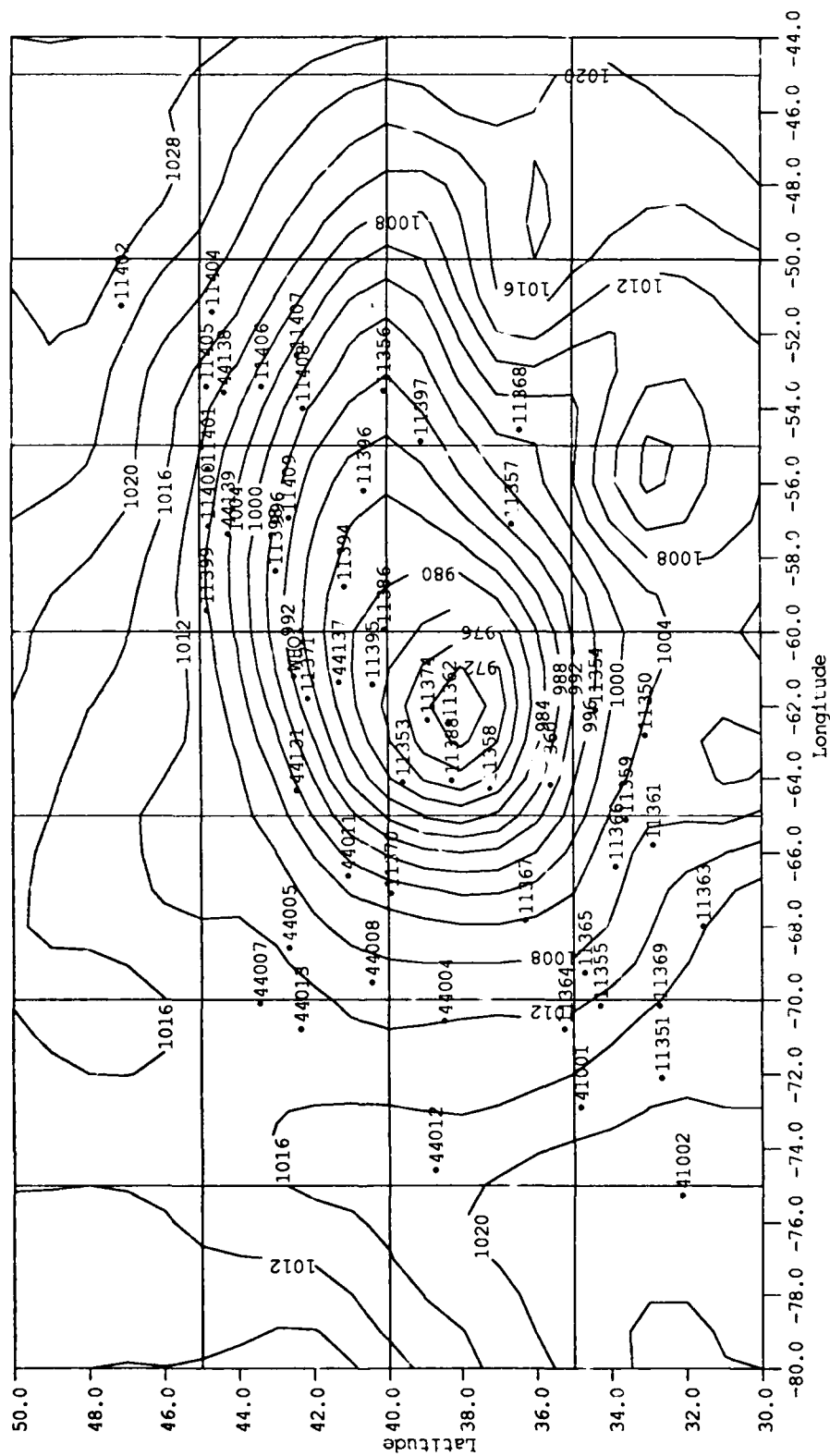
The module, ANAL, uses a first-guess field of gridded-pressure values over the ERICA region; preliminary surface analyses of ship and buoy data by Professor Fred Sanders were used, and his contour analyses were translated to gridded values manually. ANAL discards all station data outside the ERICA grid (80° to 44° west longitude and 30° to 50° north latitude) and on the border, and then interpolates (using a spline with tension technique) the gridded first-guess pressure values to the station locations. ANAL further provides grid-point pressures from the observed data using the 20 closest stations to each grid point within a chosen radius of influence and applying computed weights to the observations as an inverse square function of distance. Correlation statistics are then calculated. A new gridded pressure field (the analysis field) and its deviation from the first-guess field is then calculated along with a list of newly interpolated values, by surface fitting (the surface being a tensor product of splines under tension) at the station locations. Observed values minus analyzed values at the stations are then evaluated with respect to accuracy and representativeness. In this way, bias and data to be rejected are (mainly) objectively identified. The Laplacian field for each of the output and input pressure fields is also calculated; the Laplacian fields are of particular use in recognizing the information content in the pressure fields. The objective technique minimizes the station data to be identified as inaccurate or nonrepresentative in comparison with subjective techniques. Data lists have been prepared for the use of researchers utilizing the surface pressure data that are incorporated on the ERICA CD ROM produced by Drexel University.

Figure 1 presents a typical graphical representation of ERICA surface pressure data, with buoy positions plotted for 1800 UTC on 14 December 1988 - near the termination of ERICA IOP2. This is a time of good areal coverage by the ERICA drifting buoys during a rapidly intensifying storm of great interest to researchers. Graphics were produced on an ERICA Macintosh™ system, utilizing software named WHIZ™.

The surface pressure contours are automatically plotted from the entirety of the surface atmospheric pressure data (from moored and drifting buoys, ships, and C-MAN stations) remaining after elimination of inaccurate and nonrepresentative ship reports. No buoy reports were found either inaccurate or nonrepresentative. Five ship reports were found to be either too high or too low, in amounts ranging from 3 to 17 mbar. Further, for the entirety of IOP 2, three ships were found to be biased in their reporting of surface pressure, in amounts ranging from 2 mbar too low to 3 mbar too high. The rejected reports represent only a very small fraction of the 129 marine station pressure reports available for 1800 UTC, 14 December 1988 in the ERICA region (80° to 44° west longitude, 30° to 50° north latitude).

Drifting (11xxx series) and moored (41xxx and 44xxx) buoy positions are plotted on the pressure contour chart in Figure 1; the ship and C-MAN positions are available, but not plotted here. It is noted that seven ERICA drifting buoys are located inside the 980-mbar contour, near storm center. This detailed coverage, achieved by judicious spatial and temporal air deployment of the buoys, accomplished the intent and objectives of the ERICA drifting-buoy program.

88121418 ALL DATA
Contour range
Int. from to
4.0 964.0 1036.0



The Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) Field Research Project; Objectives, Hypotheses and Planning

Page 1A

Ron Hadlock¹

Carl W. Kreitzberg²

Abstract

The Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) field study is designed to determine physical mechanisms and processes and their critical spatial and temporal combinations, which can account for the wintertime phenomenon of explosively-developing over-ocean atmospheric storms. Theoretical and numerical modeling research, during the five-year Office of Naval Research (ONR) Heavy Weather at Sea Accelerated Research Initiative ERICA program, comprises continuing effort, including the field study scheduled for 1 December 1988 - 28 February 1989. The ONR core field experiment will be supplemented by the substantial participation of many other agencies and universities from the United States and Canada. Data will be obtained over the North Atlantic Ocean from Cape Hatteras to beyond Newfoundland, centered east of Cape Cod and south of Nova Scotia. The general timing and siting is chosen through consideration of historical storm occurrence data. Measurements on individual rapidly-intensifying storms will be made from aircraft, buoys, and satellites, and by soundings and radars. Observations made during the pre-ERICA field test, January 1988, are discussed. This article describes the measurement objectives and the ways by which the field data will be collected.

1. Introduction and background

The Office of Naval Research (ONR) initiated and base-funded the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) for a five-year duration, 1986 to 1991. The objectives of the program are to: (1) understand the fundamental physical processes occurring in the atmosphere during rapid intensification of cyclones at sea, (2) determine those physical processes that need to be incorporated into dynamical prediction models through efficient parameterizations if necessary, and (3) identify measurable precursors that must be incorporated into the

¹ ERICA Field Director, Battelle Ocean Sciences, Richland, Washington 99352.

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initial analysis for accurate and detailed operational model predictions. The producing of tools such as improved operational numerical analysis and prediction models is not a part of ONR's basic research initiative; such follow-on work will be done in other programs and is of central concern to several organizations participating in the field study.

ERICA is part of the ONR Marine Meteorology Accelerated Research Initiative's Heavy Weather at Sea Program. In turn, ERICA consists of two interacting components: (1) theoretical, numerical modeling, and analysis studies and (2) field measurements. The acronym "ERICA" has become used equally for the whole program and for the 1988-1989 field study. Research instrumentation and support of personnel within the Genesis of Atlantic Lows Experiment (GALE, to which ERICA is linked as a follow-on field study) and the Canadian Atlantic Storms Program (CASP), both conducted from January to March 1986, have also been provided by the ERICA program.

Scientific study of rapidly intensifying over-ocean cyclones ~~will~~ have occupied only about a decade when the ERICA program is completed (see References). In the seminal paper on storm climatology and characteristics Sanders and Gyakum (1980) used the term "meteorological bomb," which they defined as "an extratropical surface cyclone whose central pressure fall averages at least 1 mb h^{-1} for 24 h" (normalized for 60-degree latitude). Research has continued on storm climatology and structure (Sanders 1986a), numerical studies and evaluations (Sanders 1986b; 1987), and dynamical and case studies (Nuss and Anthes 1987; Rogers and Bosart 1986; Uccellini 1986). These papers cited are recent contributions in each area.

One reason for ERICA's merit is the history of death, damage, and expense that these storms are known to have caused. Commercial shipping and fishing have been disrupted, drilling rigs have been capsized, ocean liners and naval vessels have been damaged, and naval sea and air operations have frequently been hindered. With development of better position, motion, and intensity forecasting, it is likely that the storms will cause less havoc because better evasive and preparatory actions will be possible. Past numerical forecast schemes have been imperfect because the storms are relatively small in size and develop rapidly, because the physical processes and structure are not fully understood, and because data from over the oceans are relatively few. The ERICA research will have fundamental value in producing new scientific understandings which will be applied to improve forecasting.

The ONR ERICA Steering Committee³ first met in November 1985, to begin the process of defining research opportunities and potential problems, and to develop scientific hypotheses to be tested. The importance of joint meteorological and ocean-surface data acquisition was recognized early in those deliberations. Most members of the Steering Committee then participated in either GALE or CASP. A general scientific hypothesis for ERICA was formulated in May, 1986:

Rapidly intensifying extratropical cyclones occur principally in the western portions of the major ocean basins during the cool season. These storms may persist for several days and adversely affect maritime interests over a substantial region. The explosive deepening phase of these cyclones tends to occur on temporal and spatial scales of a few hours and a few hundred kilometers with deepening rates of ten millibars or more per six hours. Such development requires a unique interaction of synoptic, mesoscale, and boundary-layer processes.

Sensible and latent heat fluxes in the marine boundary layer are crucial in generating a low static stability environment, with locally enhanced equivalent potential temperature favorable for intensification on a small scale. Frontogenetic processes along the ocean surface temperature boundaries of the Gulf Stream or along the coastal baroclinic zone can induce thermally direct circulations which help to generate concentrated regions of vorticity-rich air in this low static stability environment.

At the time of explosive deepening there is intense cyclonic vorticity advection aloft over the surface cyclone center. Organized convective disturbances may contribute substantially to cyclonic vorticity growth through a positive feedback process involving marine boundary-layer convective-scale circulations and the larger-scale vertical circulation. This feedback process is enhanced by the favorable superposition of the updraft region of a mobile short-wave trough or jet streak over the vorticity-rich lower troposphere.

Utilizing experience and ideas from GALE/CASP, it was recognized that testable subhypotheses would be required. This led to the first ERICA Workshop, held at Drexel University in September 1986, at which prelimin-

³ The composition of ONR's Steering Committee is: Bob Abbey, ONR; John Bane, University of North Carolina; Lance Bosart, State University of New York at Albany; Greg Forbes, Pennsylvania State University; Ron Hadlock (chairman), Battelle Ocean Sciences; Carl Kreitzberg, Drexel University; Steve Lewellen, Aeronautical Research Associates of Princeton; Rao Madala, Naval Research Laboratory; Fred Sanders, Marblehead, Massachusetts; Joe Schaefer, National Weather Service; Ron Stewart, Atmospheric Environment Service; and Chuck Wash, Naval Postgraduate School.

ary subhypotheses suitable for programmatic testing were developed by about 70 participants. The subhypotheses were produced for three atmospheric scales - cyclonic, mesoscale, and boundary-layer, and for air-sea interaction. The ERICA Overview Document was published in March 1987. Ten seasons (1976-1985) of rapidly-intensifying storm occurrences were compiled and the data (from the National Meteorological Center 3-hourly North American surface weather charts, microfilm version) were published in the ERICA Storm Atlas, Volume 1, in July 1987. A total of twenty-two seasons of storm data (1966-1987) have more recently been compiled. The North American chart data have been supplemented by the Northern Hemisphere chart data, marine data from ships and buoys, and the relevant upper-level data in Volume 2 of the ERICA Storm Atlas. The ERICA Field Implementation Plan (FIP) was distributed in November 1987, following the ERICA FIP Workshop at Battelle Ocean Sciences, Duxbury, Massachusetts in September 1986. The FIP contains refined scientific hypotheses, the scientific plan for accomplishing the objectives, and a limited discussion of field operations plans. The ERICA Field Operations Plan (FOP) was distributed in July 1988, following a field test and two workshops.⁴ In early 1988, field tests of new dropwindsonde and drifting buoy systems were conducted under wintertime North Atlantic storm conditions.

2. Scientific issues and data requirements

The objectives of ERICA and the steps taken while designing the field study have been outlined in section 1. Hypotheses were solicited and compared with available evidence, and data requirements for hypotheses testing were compared with feasible data collection strategies. A detailed storm climatology was developed to determine the areal coverage, time, and duration of the field study. The detailed storm climatology shows clearly the existence of the ERICA phenomenon: abnormally rapid growth of winter cyclones over a remarkably small portion of the northwest Atlantic Ocean. Since the abnormal growth rate is rare over land and since data are scarce over oceans, there are many hypotheses, but little hard evidence, on the mechanism or mechanisms responsible for the ERICA phenomenon.

⁴ The FOP incorporates the efforts of ERICA's Field Operations Team: Ralph Anderson, NOAA/NESDIS; John Bane, University of North Carolina; Bob Black (colonel), Office of the Federal Coordinator for Meteorology; Geoff DiMego, NOAA/NMC; Neil Estela (lieutenant), NAS Brunswick; Greg Forbes, Pennsylvania State University; Ron Halllock (chairman), Battelle Ocean Sciences; Carl Kreitzberg, Drexel University; Jim McFadden, NOAA/OAO; Ray Partridge, CNOC; Jim Perkins (major), USAF/AWS; Joe Schaefer, NOAA/NWS; Ron Stewart, AES; Sam Trunzo (lieutenant colonel), USAF/41RWRW, and Chuck Wash; Naval Postgraduate School.

The general scientific hypothesis stated in section 1 contains the ingredients of most of the specific hypotheses that have been proposed, but the relative importance of different ingredients remains in dispute. ERICA researchers generally agree that strong lower-tropospheric baroclinity, low static stability and ample moisture are necessary for the abnormally rapid growth rate. Debate continues on issues including the roles of evolution of subcyclonic-scale structure, vertical coupling mechanisms and synergistic effects, interaction of pre-existing disturbances, subcyclonic-scale hyperbaroclinic zones and jet streaks, convection and release of potential instability, and details of the sea-surface temperature distribution.

Figure 1 depicts in plan section features that could interact during the rapid intensification phase. The mechanism of rapid surface-pressure fall ahead of the wave cyclone could be dominated by lower-tropospheric features after being triggered by middle- or upper-tropospheric features. The development could be a normal response to abnormally strong forcing, for example from abnormally strong low-level baroclinity. Alternately, the development could be an abnormal response to normal forcing, for example due to abnormally low static stability or to synergistic interactions whereby the latent heat release results in strong vertical coupling of cyclogenetic mechanisms.

Figure 2 from the ERICA Storm Atlas shows the tracks of 104 storms, during 22 winter seasons, that met the ERICA criterion of at least 10 millibar deepening per 6 hours for at least 6 hours. Figure 3 shows the distribution of pressure falls in these storms; the 3-hour pressure falls in each 2-degree latitude/longitude square have been summed. It is clear that the ERICA phenomenon is strongly focused in the region north of the Gulf Stream and south of Nova Scotia where the sea-surface temperature gradient is strong. However, the strongest sea-surface temperature gradient is in the GALE area near Cape Hatteras, where many storms form initially but do not deepen at their most rapid rate. This evidence suggests, and individual charts confirm, that the low-level air ingested into the rapidly moving and deepening storms had been cold air from eastern Canada that was drawn southward by the preceding cyclone over the cool water and warmed and destabilized. In many cases, this air is still colder than the water. In other cases, the air ingested at low levels into the rapidly deepening storm is warm air moving northward over progressively colder water above a shallow inversion that isolates the surface boundary layer from the storm aloft. But when does the sea-surface temperature influence the cyclogenesis? Is it a case of pre-conditioning by surface fluxes that lowers the static stability and

then permits rapid development, or is there an immediate linkage between the surface fluxes and the convective transport to higher levels?

Figure 4 is the frequency distribution of the maximum 24-hour pressure falls in the 104 ERICA-type storms. There is clear indication of a peak in frequency near 35 millibars per 24 hours that suggests a distinct cyclogenetic mechanism, as discussed by Roebber (1984). Is this peak a normal response to the enhanced low-level baroclinity induced by the sea-surface temperature gradient or is it an abnormal response due to a distinct mechanism, perhaps due to synergistic effects?

Figure 5 shows the distribution of the storms in two-week periods during the winter season. The frequency peaks around the first of the year when the continental air is the coldest. This evidence suggests that the strength of the low-level baroclinity between Nova Scotia and the Gulf Stream strongly influences the frequency of the storms.

Figure 6 shows the year-to-year variation in the occurrence of ERICA-type storms. There are very active seasons and very inactive seasons and, within any season, there are prolonged periods of high activity and low activity. This information is useful in planning the field study because it shows that a given quota of storms may be reached in as few as 6 weeks or it may take up to 12 weeks; preparation is required for a long field program but it may be finished early.

The search for other instability mechanisms to explain the abnormally rapid deepening leads to the following set of questions. Is the release of potential instability (vertical or slantwise) responsible for the rapid deepening? Is the instability released only along narrow frontal bands? Does the destabilization from surface fluxes ahead of the storm result in far more convection along the warm front than in continental cases that can then result in faster moving and faster deepening storms?

The issues discussed above and the hypotheses that follow therefrom form the basis of the observing system design for the field study. It is possible that different storms develop as the result of different mechanisms. Therefore, it is hoped that eight cases of significant cyclogenesis can be studied, half of which deepen at the ERICA rate and half of which provide counterexamples. To observe this many cases a three-month program must be planned; also, plans must be in place to complete the field study early should a very active season occur. The study area should extend from the vicinity of the Gulf Stream to North America and to just east of Newfoundland Island.

Since this phenomenon occurs in an oceanic region normally devoid of observations aloft, emphasis should be placed on observations in the developing storm, with less emphasis on enhancing upwind observations

over the land. To observe storms throughout this region, broad coverage by surface buoys and airborne instrumentation is required. Final conclusions are likely to require comparison with numerical simulations so knowledge of the vertical structure throughout much of the troposphere will be required. Therefore, dropwindsondes are of central importance. Weather reconnaissance aircraft missions around the storm will be required to provide information on the cyclonic-scale environment that is required for numerical simulations. Since latent heat release could be crucial, airborne radar data are also of central importance.

Boundary-layer data are likely to be of most value ahead of the storm, at least in space and possibly in time. The shallow inversion that exists when warm air flows over colder water will be beneath the lowest aircraft, so dropwindsondes must have detailed vertical resolution. Surface data beneath the aircraft will be vital. Real-time ship observations are too sparse to document the early stages and deepening rates of the storms, so the real-time buoy data will be the key to nowcasting for aircraft operations. Rawinsonde data near the coast will require additional stations and soundings at 3-hour intervals and even hourly intervals when the storms cross Nova Scotia. Further inland to the West and North, rawinsonde data obtained at 6-hour intervals from existing sites and automated commercial aircraft reports should prove adequate.

There are valid data requirements that can be stated but not fully met with current resources and technology. For example, enhanced surface observations of relative humidity, wind, and waves at a hundred points over the ocean can be justified but cannot be obtained. Aircraft observations in the boundary layer can partially fulfill this need. Jet stream structure over the explosively developing storms far offshore can not be observed by available research aircraft. Nevertheless, it is clear that the observations that can be obtained will greatly expand the ability to validate numerical simulations and identify mechanisms responsible for rapidly-intensifying winter cyclones between the Gulf Stream and North America. The challenge will be to optimize research aircraft observations when the desired conditions occur.

Figure 7 shows schematic pressure fall with time in the central storm region, associated with rapid intensification. Pressure fall is the physical phenomenon which will dictate much of the schedule of measurements for a storm. Research flights and special soundings will be activated so that adequate sampling is done for the explosive phase, as well as before and after. The intensive observation periods (IOPs), with expected durations of 36 hours, will incorporate at least the initiation and explosive phases of storm development.

3. Multi-agency participation

ERICA is made possible only by the participation of many agencies (see Appendix). The Office of Naval Research, Marine Meteorology Program, was the lead agency in conceiving the ERICA research program and provides core funding in the amount of about \$3.6M for FYs 1988 and 89 field study costs including principal investigator contracts at universities and research organizations, measurement systems and expendables, and operations expenses. Other organizations have joined as participants to plan, provide resources, and implement the field phase.⁵

4. Field program, observing systems, and networks

a. Field program

The ERICA field phase will be conducted from 1 December 1988 through late in February 1989 with a holiday operations break from 1200 UTC 22 December through 1200 UTC 27 December. The actual termination date will be decided in the field, by the ERICA field director, based on the acquired number of completed and successful encounters with storms and by the amount of remaining measurement resources. It is apparent, based on the ERICA Storm Atlas data and the need for detailed measurements on approximately four ERICA-type storms and an equal number of less explosive storms, that the field phase work will reach high intensity early in December.

Field operations will be directed from facilities provided by the National Meteorological Center (NMC) and National Environmental Satellite, Data, and Information Service (NESDIS), major ERICA participants, at the World Weather Building, Camp Springs, Maryland, and from the Maritimes Weather Centre, Bedford, Nova Scotia. ERICA and NMC work together on forecasting and nowcasting and NMC and NESDIS collaborate to assure that appropriate data, including certain ERICA real-time sets, and products are integrably available.

The ERICA field study utilizes the following major sets of instrumentation systems: all conventional, operational meteorological systems employed by the United States and Canada, two WP-3D aircraft for

⁵ Agency participation in ERICA is coordinated by the ERICA Agency Coordination Executive Team: Bob Abbey, ONR; Chandrakant Bhumralker, NOAA/OAR; Bob Black (colonel), USAF/OFCM; John Cuning, NOAA/ERL; Dick Dirks, NCAR; George Isaac, AES; Carl Kreitzberg (chairman), Drexel University; Ron Lavoie, NOAA/NWS; Jim McNitt (lieutenant commander), Office of the Oceanographer of the Navy; Don Miller, NOAA/NESDIS; Steve Nelson, NSF; and Ron Hadlock (ex officio), Battelle Ocean Sciences.

LeSonde⁶ activity and mid-level flights to acquire flight-level and remote (including Doppler) data, plus an additional Navy P-3 to deploy drifting buoys and LeSondes; and high-level aircraft for obtaining flight-level data and for deploying dropsondes.

The United States Air Force (USAF) WC-130s deploy Omega dropsondes, providing thermodynamic data, and wind measurements by one of the aircraft. The National Center for Atmospheric Research (NCAR) Sabreliner documents jet stream structure near the coast; the NCAR Electra documents details in the boundary layer directly and deploys LeSondes. Other instruments used are ARGOS satellite-linked drifting buoys; existing moored buoys, augmented by Woods Hole Oceanographic Institution and AES (Atmospheric Environment Service) new deep-water moorings; supplemental and CLASS (Cross-Chain Loran Atmospheric Sounding System) rawinsondes; satellite imagery and soundings; wind profilers in Pennsylvania and Canada; conventional ground-based radars and the Air Force Geophysics Laboratory Doppler radar; surface mesonets in Canada, with stations on Sable Island and southern Nova Scotia; operational airline meteorological reports ([Aeronautical Radio (ARINC) Communications Addressing and Reporting System] ACARS and ASDAR [Aircraft-to-Satellite Data Relay]); and routine ships, encouraged to take more frequent observations.

b. Aircraft

The Naval Air Station Brunswick, Maine is the primary base for aircraft operations. Research aircraft may be staged at other locations, based on what is actually happening with respect to forecasted storms to be measured. Alternates may be required because of vagaries of storm paths and because weather will affect the availability of operating sites at times. These locations are shown on the outline map of figure 8, which generally indicates the region of ERICA measurements. The stippled area is the region of greatest summed pressure falls for the 104 ERICA-type storms, and the area which will have the highest concentration of ERICA measurements. The smoothed Continental Shelf boundary (100 fathoms) and Gulf Stream are also indicated. This map is meant only as a locator of ERICA-related places; special ERICA measurements, e.g., rawinsondes, are made to the west of the map's western border and ERICA measurements do not cover the entirety of the area shown.

Aircraft measurement represents the core of the ERICA field study that can be flexible enough to accommodate variations in storm track and

⁶ LeSonde is a new NCAR-developed aircraft-deployed, lightweight dropwindsonde package and aircraft electronics system, which use the Loran-C navigation system, to measure winds. The "L" is for Lally and Lauritsen, the principal engineers, and for Loran; the "e" is for ERICA.

structure. It is, therefore, particularly important that meteorological aircraft flights are scheduled to meet the central needs of the ERICA field study.

The USAF WC-130s, operating under the National Winter Storms Operations Plan, concentrate on the needs for cyclonic-scale data over the ocean. These missions are requested at 12-hour intervals and are nominally of 10-hour duration. The midpoints of these missions are before, during, and after the rapid intensification phase of the storm, centered on synoptic times 00, 06, 12, and 18 UTC. Data relative to these times are of equal value in NMC's Global Data Assimilation System.

The first mission is essential for documenting the pre-existing environmental baroclinity, stability, and moisture, particularly in the region containing the air that will be ingested into the storm at low levels during its rapid intensification phase. Scheduling of this mission provides the ERICA forecast team with its most important long lead-time task. For example, to be on station 12 hours prior to time 0, the beginning of rapid intensification, this mission must be tasked about 30 hours prior to time 0. A 24-hour outlook is desired, and therefore is given 54 hours prior to time 0. This outlook must be based on an 84-hour forecast because the forecast must extend 12 hours beyond time 0 for the timing to be established. The second and third missions in the IOP follow at 12-hour intervals so the difficulty in scheduling these flights depends upon whether major changes in forecasts arise after the initial outlook.

The NCAR Sabreliner missions are keyed to prediction of jet stream structures that could impact the rapid intensification phase. These structures are intercepted by the Sabreliner near the East Coast of the United States. The scheduling problem for the Sabreliner is rather specialized, but considerable success was achieved in GALE and is possible during ERICA.

The first NOAA Office of Aircraft Operations (OAO) WP-3D mission is the most difficult to schedule because of takeoff at time -6, when the cyclone position may be ill-defined. Once the aircraft locates the storm, it is able to provide invaluable guidance for scheduling subsequent missions. During the rapid intensification phase, from about time -2 to about time +6, the Navy P-3 is scheduled for a mission overlapping with OAO WP-3D missions, which document the mesoscale structure of the low-level cyclone, frontal zones, updraft zones, and convection regions. The NCAR Electra mission focuses on the boundary-layer structure feeding the rapidly intensifying cyclone. One or both of the OAO WP-3Ds is on station throughout the rapid development phase. While the Navy P-3 is on station the OAO WP-3D can be freed of responsibility for systematic LeSonde observations so that it can concentrate on mesoscale structures.

The NCAR Electra boundary-layer flight will occupy only a portion of the rapid intensification phase, so coordination of its operation with the OAO WP-3D mesoscale missions will be crucial.

Many commercial aircraft automatically record high-quality data on winds and temperature. These data are communicated about every 40 minutes to the ground through the Aeronautical Radio (ARINC) Communications Addressing and Reporting System, ACARS. These data can be used to meet some of the ERICA requirements for sounding data over the United States and coastal regions. The data are becoming routinely available in ever-increasing volumes. Because of the extreme value of these data not only for research, but also for demonstration of the data's potential for dramatically improving operational forecasting, every effort will be made to acquire the data, after the fact, from the airlines.

c. Buoys

The meteorological buoy network includes the current operational moored buoys, a deep-water moored buoy east of the center of the ERICA storm region, placed by the Woods Hole Oceanographic Institution, three AES moored buoys in the ERICA region, and about 100 special air-deployed drifting meteorological buoys. The goal for the drifting buoys has been to design a monitoring network with buoys every 200 kilometers, and with ship data complementing the buoy data. To achieve enhanced resolution in the path of the storm center, air-deployed drifting buoys can be seeded along the anticipated storm track by the Navy P-3 aircraft, or by any available patrol aircraft that can deploy sonobuoys.

The basic air-deployed buoy reports pressure, temperature, and sea-surface temperature through the ARGOS satellite every couple of hours at ERICA's latitudes; the satellite determines buoy position within 500 m. The report includes data of the previous eight hours to provide high temporal resolution (two or three observations per hour) and redundancy for reliability. The buoy system has undergone a variety of static tests and helicopter and aircraft deployments. Lifetime of a given buoy is estimated to be three to six months. Deployment performance was tested early in 1988 in the Gulf of Mexico. Deployment and data characteristics, in the Gulf Stream and in the ERICA area, are being tested throughout 1988.

Drifting buoys that are not in the Gulf Stream will not drift far, but those in the center of the Gulf Stream can travel 1000 kilometers in 10 days. Therefore, an initial network of 50 drifting buoys for the monitoring network and another 50 buoys for reseeded - to achieve 100 kilometer spacing along storm tracks, and to replace buoys that drift out of the experiment region - are required and available. Figure 9 illustrates the buoy network.

d. Ships of opportunity

The ERICA Storm Atlas, Volume 2, contains complete information on ship reports of ERICA-type storms over the past ten years. Coverage is reasonable at 6-hour intervals, but it is spotty. The need for 3-hour data enhancement is clear, even with an extensive drifting buoy network. Ship wind reports are contaminated by flow distortion around the ship, but these errors are preferable to no data. A special plan to notify ship operators about ERICA has been made through the Mariner's Weather Log and the National Weather Service (NWS) Port Meteorological Officers. Furthermore, a number of ships are equipped with meteorological systems that read out through satellites when queried. Arrangements have been made with operational weather services to obtain hourly INMARSAT (International Maritime Satellite System) data in the ERICA region during IOPs.

Quality control of ship data is of vital importance. The NWS and the European Centre for Medium Range Weather Forecasts (ECMWF) have been asked to assist. The National Climatic Data Center (NCDC) collects as many extra reports by mail as it collects reports in real time. Therefore the NCDC Marine Data File, several months after ERICA, will be a prime source of additional and corrected data. Complete, carefully controlled data sets will be prepared after the fact.

e. Soundings

The purpose of the land-based sounding network is two-fold: it must document the ERICA storms as they cross Atlantic Canada and it must document the upper-air forcing expected to trigger the offshore cyclogenesis so that dynamic models can simulate what will exist offshore during the subsequent development.

The supplemental and special sounding network consists of regular NWS rawinsonde sites, regular Canadian rawinsonde sites (both AES and military), and CLASS Loran-C rawinsonde systems that can operate at 1-, 3- or 6-hour intervals. About 500 sondes are provided for 6-hour interval and 3-hour interval soundings at selected regular NWS sites, during ERICA IOPs, at selected times. Generally, the sites extend from the East Coast west to about 95°W. Additionally, the Bermuda station takes 6-hour interval observations on request. The exact sites will be case-dependent and selected to optimize performance of the NWS Regional Data Assimilation System (RDAS). In some cases, the upper-air disturbance comes out of the Gulf of Mexico, so sites along the Gulf Coast will be more important than those along the Canadian border; in other cases the vorticity center comes out of Alberta so the more northern sites will be

selected. Supplemental soundings (about 120) from existing AES and Canadian military sites are supported by ONR to complement 6-hour interval NWS observations at 0600 and 1800 UTC. The four sites supported by AES for three-hourly soundings are Stephenville, Newfoundland; Sable Island, Nova Scotia; St. John's, Newfoundland; and Yarmouth, Nova Scotia. Five sites along the Atlantic Canada coast - Shearwater, Nova Scotia; Eddy Point, Nova Scotia; Gagetown, New Brunswick; Summerside, Prince Edward Island; and Gander, Newfoundland - and three on land along the U. S. coast - Air Force Geophysics Laboratory, Bedford, Massachusetts, BNL, Upton, New York, and NAS Norfolk, Virginia - are provided with a total of 700 (CLASS Loran-C) sondes.

The map of figure 10 shows existing rawinsonde sites of which several will be chosen (storm-case dependent) in the United States for supplementary soundings, along with several more in eastern and Atlantic Canada. The CLASS sites are also shown.

The buoy temperature and air-sea temperature difference fields, with boundary-layer profiles of temperature, humidity, and wind are quickly examined to characterize the spatial distribution of different boundary layer regimes in IOPs. The purpose of this near real-time look is to ensure that observation quality is as good as possible, and to help guide selection of future IOPs and refinement of observation techniques.

5. Field operations plans

ERICA field operations are managed by Ron Hadlock (Battelle Ocean Sciences), ERICA field director. Carl W. Kreitzberg (Drexel University), program director of ONR's Heavy Weather at Sea Accelerated Research Initiative, collaborates in the over-all field management as associate field director. The director's chief responsibility is that of planning and real-time decision-making, including calling of IOPs, to meet the ERICA field study objectives. The associate director's primary responsibility is to plan and coordinate the aircraft operations as the ERICA Aircraft Coordinator.

Information flow and decision-making are augmented in the field through a set of scheduled meetings for daily weather briefings, daily status reports, IOP reviews following each IOP, and scientific reviews every three weeks.

About twenty five technical and managerial personnel are required to provide 24-hour staffing for the Operations and Forecast/Nowcast Centers at the World Weather Building. Between the IOPs some measure of reduced

manpower is possible. At the ERICA Aircraft Operations Center, NAS Brunswick, Airborne Mission Scientists, each with three technical assistants, are designated for each of the four WP-3D aircraft crews. Additional ERICA personnel there bring the total to about twenty five. The number of intensely-involved personnel in ERICA, from a management perspective, in addition to aircraft flight, ground, and management crews, totals to about 50, working at the World Weather Building, NAS Brunswick, and the Maritimes Weather Centre. This sum does not include remotely-located systems operators, such as for CLASS and supplementary soundings. The full complement of ERICA field study related personnel is about 150.

Eight IOPs, each of probable 36- to 48-hour duration, are expected, based on ERICA Storm Atlas climatology, between 1 December 1988 and at such time in February 1989 as resources are expended.

Figure 11 shows anticipated (scenario) IOP activity on time-lines of aircraft, sounding, forecast and evaluation, and storm development activity. "Time 0" indicates the beginning of predicted rapid intensification. The figure is constructed for a storm (7 January 1977) described in the ERICA Storm Atlas. Operational forecasting, nowcasting, measurement activities, and their interrelationships are indicated.

6. Data streams and data management

Planning and implementation of how the various data get from the acquisition instruments to the users is critical to the success of ERICA, by ensuring the quality, maintenance, and extensive use of the ERICA data. The term "data stream" is used to indicate the step-wise procedure. A set of raw data acquired by a calibrated, tested, and accepted measurement system is susceptible to several processes in the stream; these include, but are not necessarily limited to editing and formatting, quality assurance, assimilation and synthesis, archiving, and distribution.

The ERICA field study benefits considerably from the GALE and CASP experience. Specifically, the accomplishments of GALE at the GALE Data Center at Drexel University serve as a successful model of the data streaming process. Drexel performs similar work for ERICA at its ERICA Data Center. The data management objectives are to organize collection of all data of interest to ERICA, including data collected by special systems as well as conventional meteorological and marine data, support operations and forecasting functions in the field, prepare timely preliminary data sets and analyses, identify/obtain concurrence on validation procedures used by participants in data preparation, maintain

and provide an ERICA Data Catalog, make available validated data sets, as soon as possible, to all participants, and ensure the long-term availability of the data, through the ERICA Data Archive, to the entire scientific community.

The integrated collection of data and data products that will be available from the ERICA Data Center (EDC) includes both digital products and microform, hardcopy, and other products for all measurement systems employed in ERICA. The EDC will provide documentation of data collection and processing, aircraft data, sounding and dropwindsonde data, ship, buoy, and land surface observations, radar data, and satellite data.

7. Pre-ERICA field test

The pre-ERICA field test was conducted in late January 1988, with most of the measurement activity concentrated on 25-26 January. The test storm occurred during a three-month period of conducting simulation IOPs by real ERICA storm forecasting, resultant project director action, and resultant simulation response by the National Oceanic and Atmospheric Administration and OAO, with successful communication via electronic mail on OMNET.

Project Director Office and forecast/nowcast activities were located at the World Weather Building, Camp Springs, Maryland, and at Drexel University; OAO WP-3D aircraft operations were operated from Naval Air Station Brunswick, Maine; and USAF WC-130 National Winter Storms Operation Plan (NWSOP) missions, requested by NMC, were operated from Keesler Air Force Base, Mississippi. Certain communications were tested, including telephone and hard-copy telemail links among those locations and with the Maritimes Weather Centre and the University of Washington, a telephone patch to the WP-3D while in flight, and the Hurricane Hot Line. ERICA forecast/nowcast procedures were successfully tested, with useful input from NMC and NESDIS personnel in facilities provided by these organizations at the World Weather Building. Tests on drifting buoys were conducted from January to March 1988 by the Naval Ocean Research Development Activity, for launch performance in the Gulf of Mexico and for data performance in northwestern Atlantic waters.

The intensive activity was directed to measurement on a rapidly intensifying winter storm in the northwestern Atlantic in and near the region over which ERICA field study measurements are scheduled. Two OAO WP-3D research missions and three WC-130 reconnaissance missions were accomplished. The storm structure was studied from Cape Cod across the

Gulf of Maine to Nova Scotia, and across the Gulf of St. Lawrence to Newfoundland. The WP-3D flights, which incorporated successful tests of the new NCAR LeSonde system, concentrated on precipitation regions that cause intensification. Also, the storm center was examined at three points: start, during, and end of extreme deepening. For the first time the complete cycle of extreme oceanic storm intensification has been observed by the same scientific personnel, within the storm. The NWSOP flights provided valuable flight-level data and dropsonde data for short-term forecasting and nowcasting as well as for understanding the pre-conditioning of air entering the storm.

The pre-ERICA storm observations generated some preliminary general findings. Bermuda-type air present off Cape Cod and just south of Newfoundland resulted in the extreme temperature gradient that permitted the rapid storm growth; a strong temperature inversion in the first 150 meters isolated the atmosphere from the lower boundary layer thereby creating a free slip boundary condition for the storm. Widespread intense turbulence was found in the center of the mature storm, which had no precipitation. A change was observed in the Gulf of St. Lawrence's surface, from ice-covered before the storm to open water with high waves during the storm. The storm developed completely within 24 hours, moved at 45 knots, and had wind speeds of 150 knots at 5.8 km, well below the jet stream that probably had speeds close to 225 knots. For contrast, note that hurricanes are far less frequent in any location, form over a period of many days, and generally travel at about 15 knots.

Appendix. Organizations Participating in ERICA

Department of Defense

Office of Naval Research, Arlington, Virginia

Naval Postgraduate School, Monterey, California

Naval Research Laboratory, Washington, D.C.

Oceanographer of the Navy, Washington, D.C.

Commander Naval Oceanography Command, NSTL, Mississippi

Naval Eastern Oceanography Center, Norfolk, Virginia

Naval Oceanography Command Facility, Brunswick, Maine

Naval Ocean Research and Development Activity, NSTL, Mississippi

Naval Air Station, Brunswick, Maine

Naval Air Development Center, Warminster, Pennsylvania

Air Force Military Airlift Command

41st Rescue and Weather Reconnaissance Wing, 41RWRW,
McClellan AFB, California

Air Weather Service

Air Force 53rd Weather Reconnaissance Squadron,
Keesler AFB, Mississippi

Air Force Geophysics Laboratory, Hanscom AFB, Massachusetts

Air Force Office of Scientific Research, Bolling AFB, Washington, D.C.

Marine Corps, Washington, D.C.

Department of Commerce

National Weather Service, Silver Spring, Maryland

National Meteorological Center, Camp Springs, Maryland

Eastern Region, Garden City, New York

Central Region, Kansas City, Missouri

National Ocean Service, Washington, D.C.

Ocean Products Center, Camp Springs, Maryland

National Environmental Satellite, Data, and Information Service,
Camp Springs, Maryland

National Climatic Data Center, Asheville, North Carolina

Environmental Research Laboratory

NOAA/ERL and NSF/NCAR STORM Project Office, Boulder, Colorado

Office of Aircraft Operations, Miami, Florida

Department of Transportation

United States Coast Guard

Department of Energy

Brookhaven National Laboratory, Upton, New York

National Science Foundation

NCAR Research Aviation Facility, Boulder, Colorado

NCAR Office of Field Project Support, Boulder, Colorado

Atmospheric Environment Service, Toronto, Canada

Federal Panel on Energy Research and Development, Ottawa, Canada

European Centre for Medium Range Weather Forecasts,
Reading, England

**Office of the Federal Coordinator for Meteorological Services and
Supporting Research**, Washington, D.C.

Universities and Research Organizations

Drexel University, Philadelphia, Pennsylvania

Pennsylvania State University, University Park, Pennsylvania

State University of New York, Albany, New York

Naval Postgraduate School, Monterey, California

Massachusetts Institute of Technology, Cambridge, Massachusetts

University of California, Irvine, California
 University of California, Los Angeles, California
 University of Washington, Seattle, Washington
 University of Wisconsin, Madison, Wisconsin
 North Carolina State University, Raleigh, North Carolina
 Yale University, New Haven, Connecticut
 McGill University, Montreal, Canada
 Woods Hole Oceanographic Institution, Woods Hole, Massachusetts
 ARAP/Titan, Inc., Princeton, New Jersey
 Battelle Ocean Sciences, Duxbury, Massachusetts and Richland, Washington

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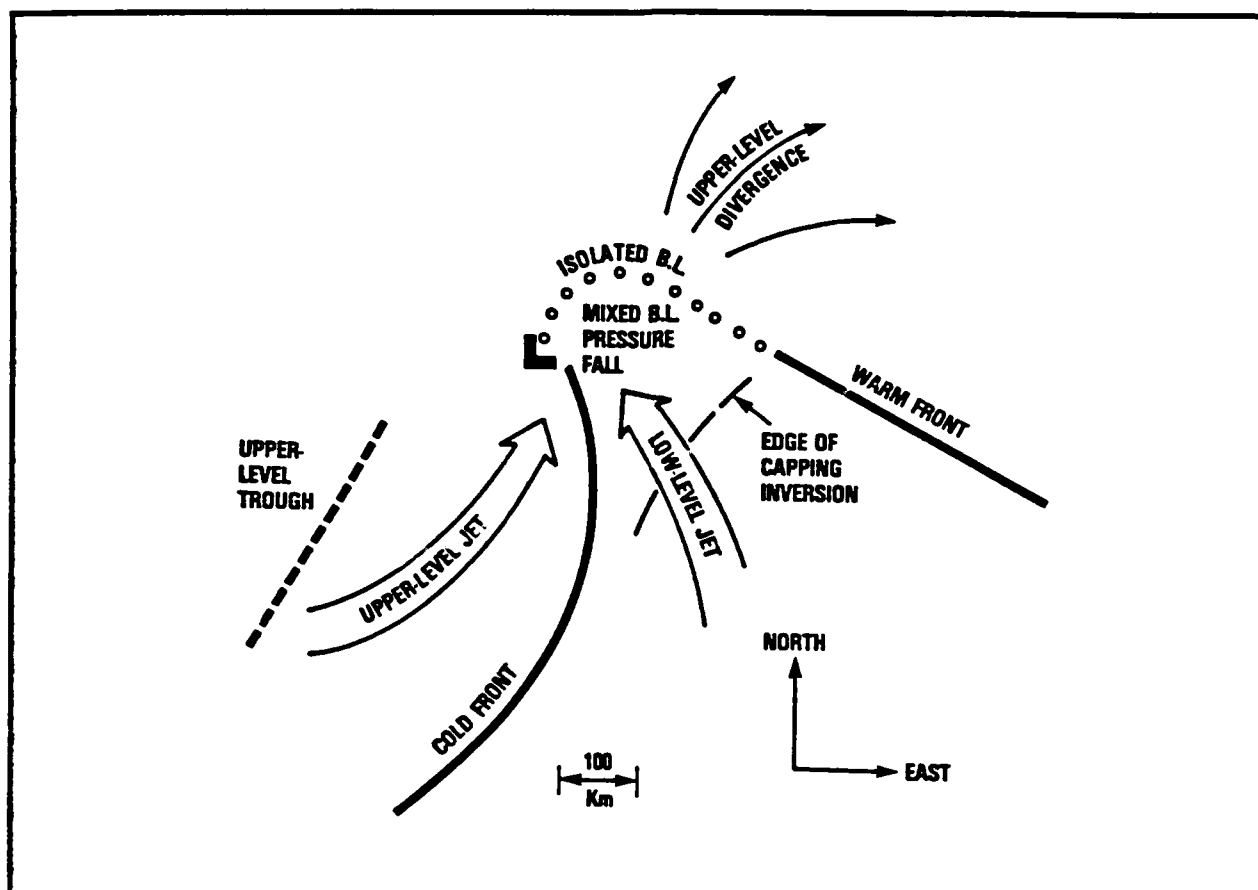


FIG. 1. Scale-interaction concepts, a schematic-storm plan view. B.L. is an abbreviation for atmospheric boundary layer.

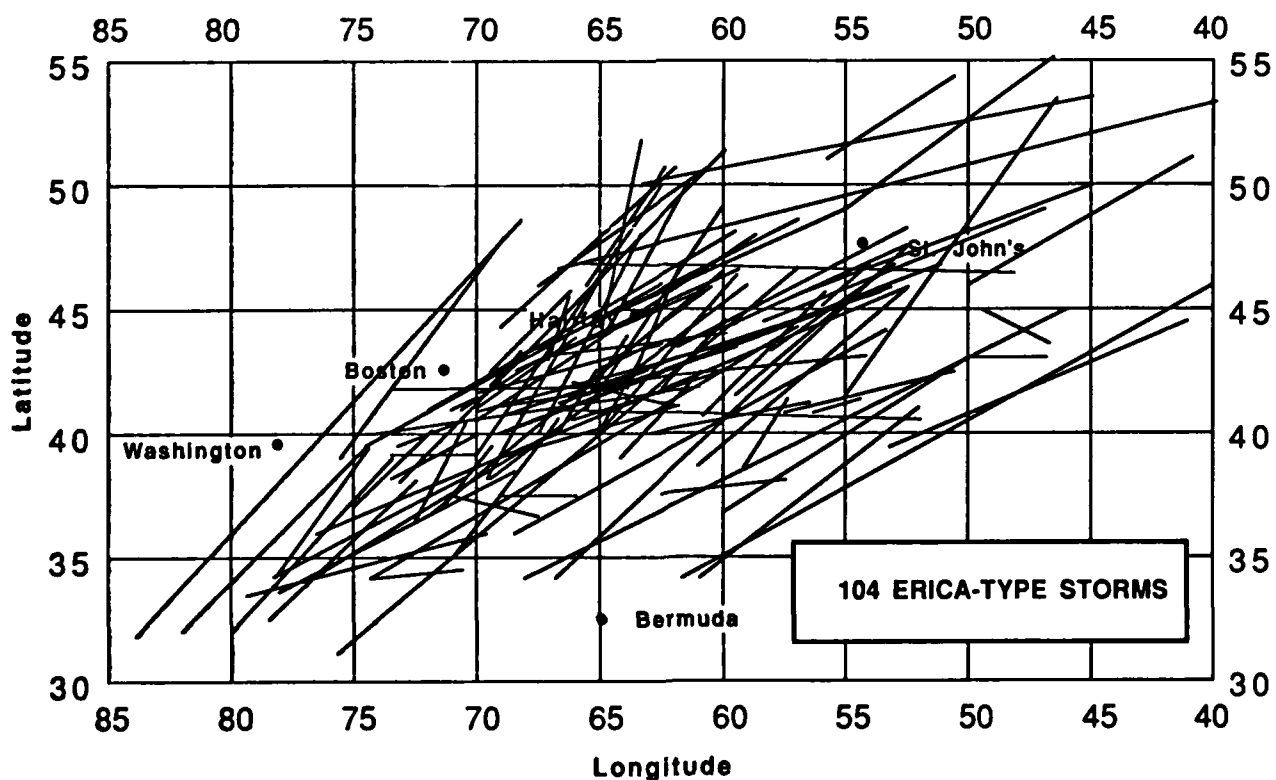


FIG. 2. Tracks (straight lines drawn between the beginning and ending of rapid development) for 104 ERICA-type maritime storms during 22 winters (1966-1987).

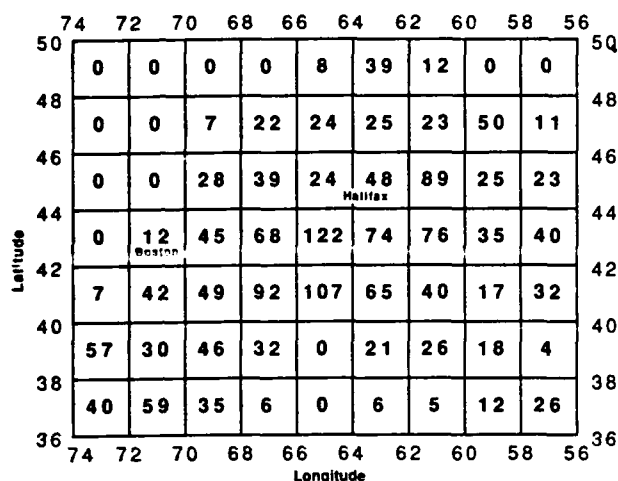


FIG. 3. Summed 3-hourly central pressure falls for the storms of figure 2 that had tracks that crossed the 36–50N, 56–74W grid of 2-degree squares.

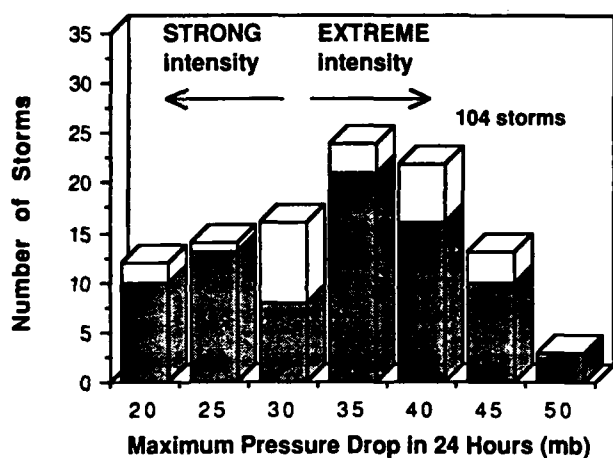


FIG. 4. Distribution, by intensity of development, of 104 storms which occurred during the winter seasons 1965–1987, between 1 December and 29 February. The shaded portions of the bars represent the subset of those storms (a total of 81) which occurred between 16 December and 15 February.

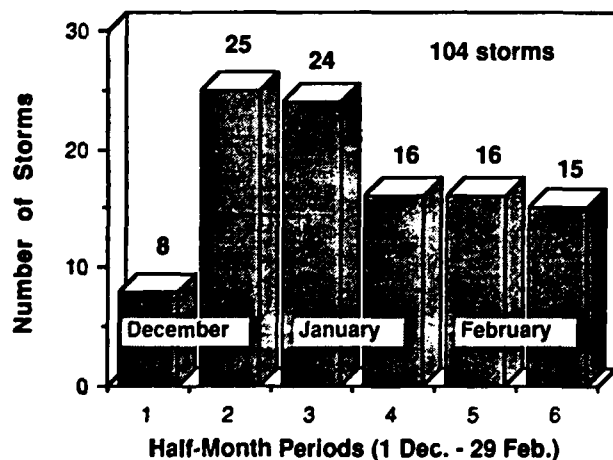


FIG. 5. Temporal distribution, in two-week periods, of 104 ERICA-type storms during 22 winters (1966–1987).

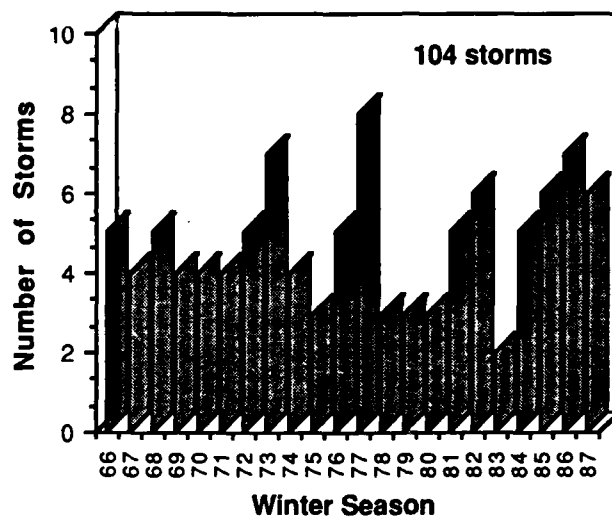


FIG. 6. Distribution, by year, of 104 ERICA-type maritime storms during 22 winters (1966–1987).

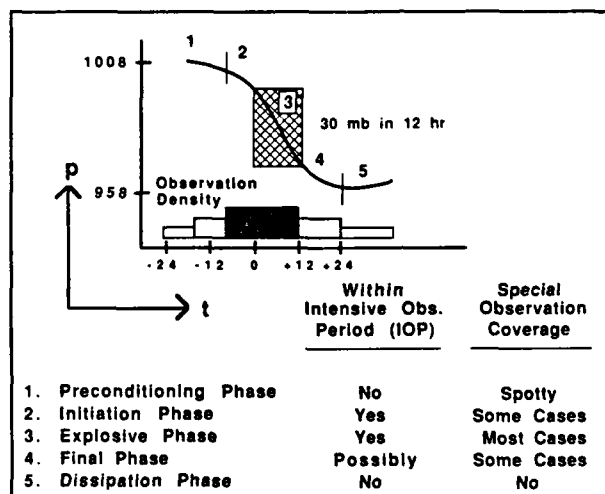


FIG. 7. Special observations before, during, and after rapid intensification. The number (density) of special observations is maximum during about 20 hours, starting eight hours prior to the beginning of Phase 3 (the rapid intensification).

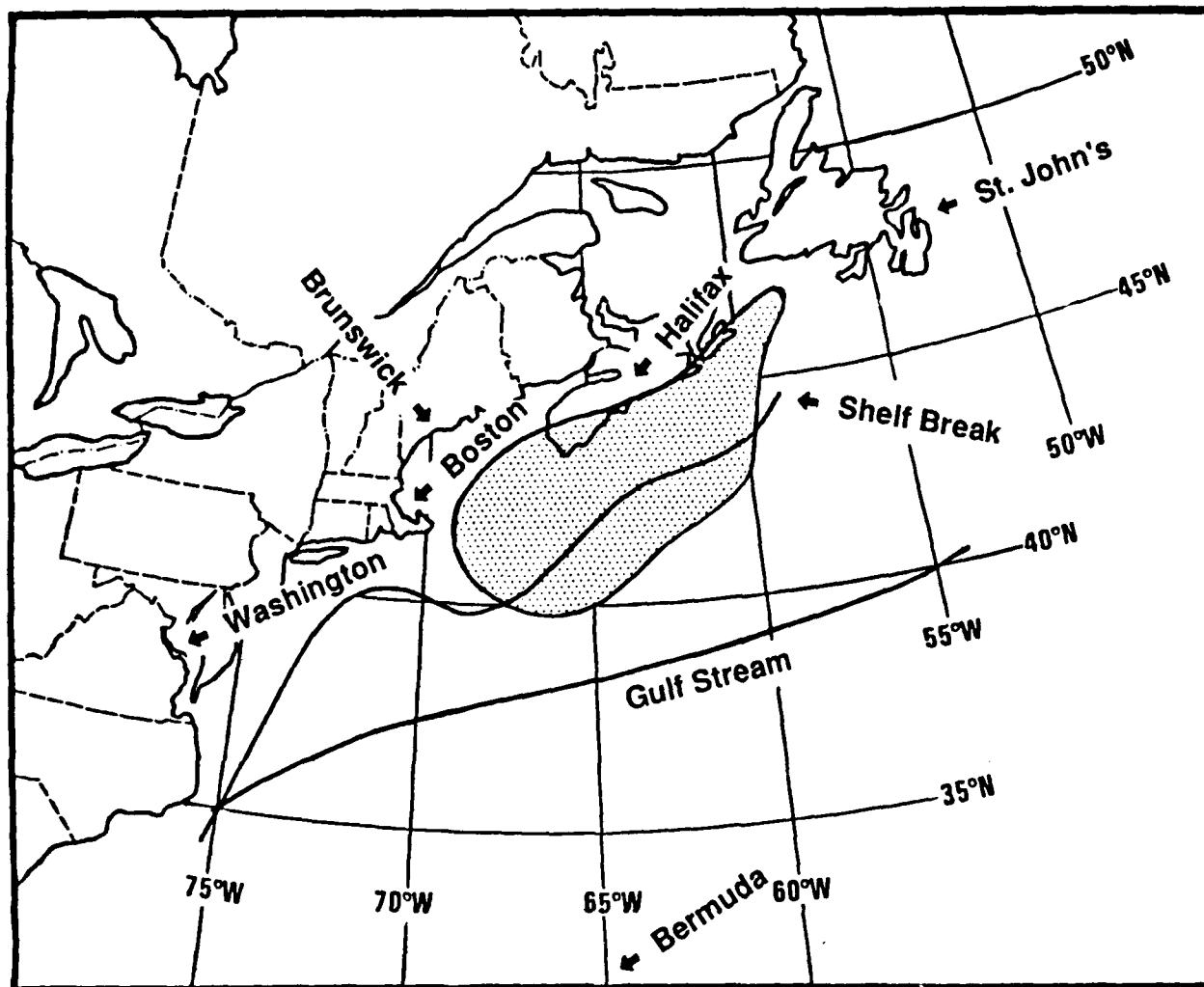


FIG. 8. The ERICA region. Stippling denotes the area of greatest surface atmospheric pressure falls for ERICA-type storms. The smoothed Continental Shelf boundary (100 fathoms) and the Gulf Stream mean position (to the south) are also shown.

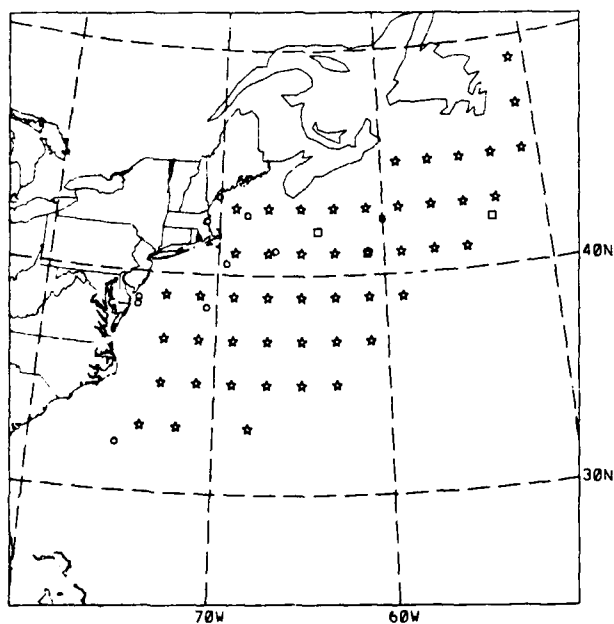


FIG. 9. Map of the ERICA buoy pattern. Stars are the planned initial deployment array of 48 drifting buoys (about 200 kilometer spacing). Circles are existing moored buoys, primarily in coastal waters. Four deep-water moored buoys are indicated by squares (AES open squares at 41°N, 61°W; 42°N, 64°W; and 42.2°N, 53.3°W, and (WHOI closed square at 42.4°N, 60.0°W).

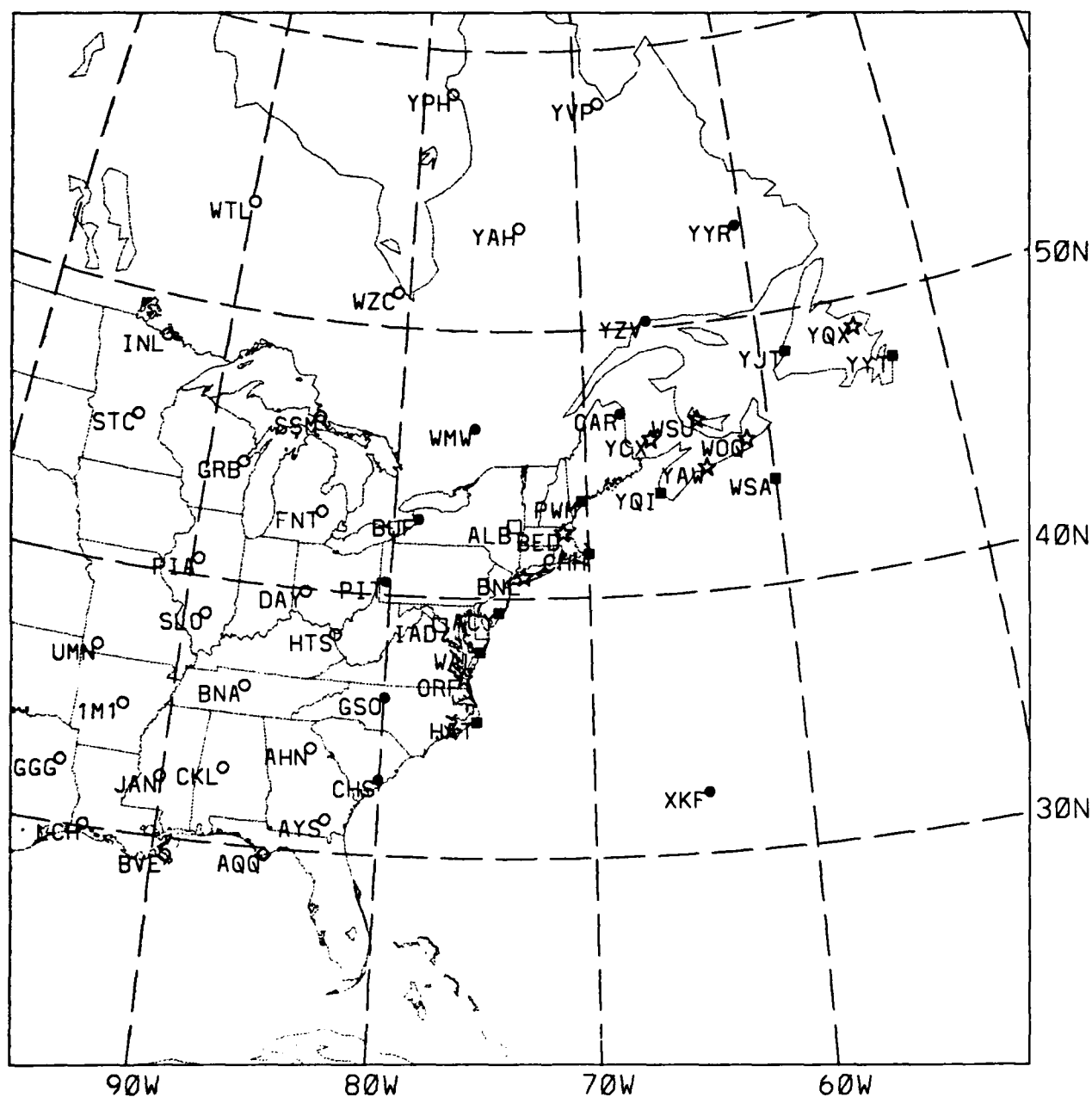


FIG. 10. Map of the ERICA sounding sites. Circles and squares are regular U.S. and Canadian sounding sites. Open circles indicate those sites at which 6-hour interval soundings may sometimes be requested. Closed circles are the U.S. and Canadian regular sites at which supplementary soundings are usually taken at 6-hour intervals. Sites at which 3-hour interval soundings are usually taken are indicated by closed squares. The open squares are two sites at which 3-hour interval soundings are sometimes requested. Eight stars are CLASS sites.

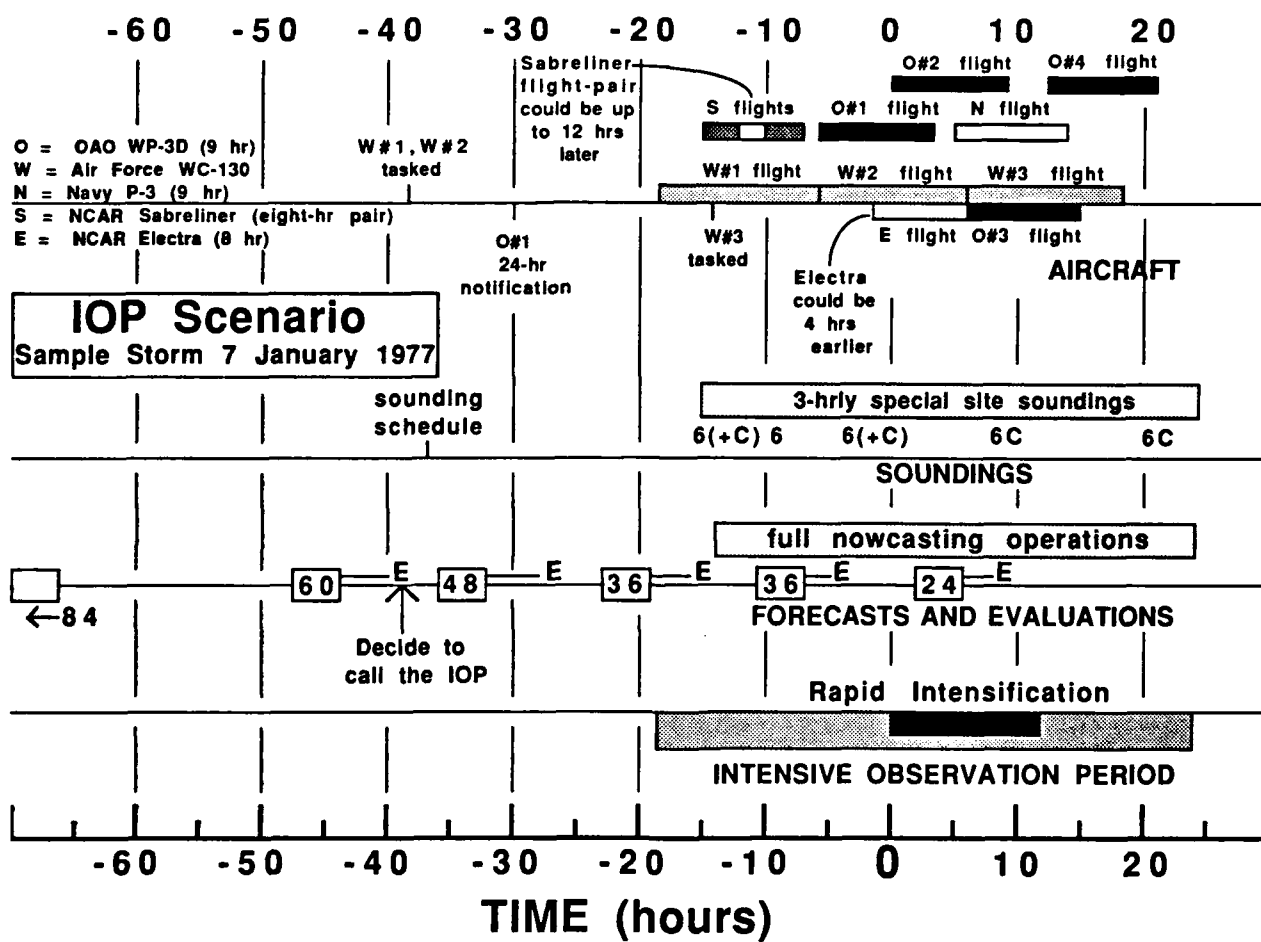


FIG. 11. Intensive Observation Period (IOP) scenario. Time lines of: aircraft activity, sounding, forecast and evaluation, and storm development activity are shown. Time 0 indicates the beginning of rapid intensification.

Overview of the ERICA Field Phase

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1. Introduction

The winter season 1988-89 provided a fortunate number of oceanic cyclones accessible to planned measurement efforts and appropriate to the objective of ERICA. The Office of Naval Research Accelerated Research Initiative, Experiment on Rapidly Intensifying Cyclones over the Atlantic, was designed to understand the fundamental physical processes occurring in the atmosphere during rapid intensification of cyclones at sea. During the field study, from 1 December 1988 to 26 February 1989, eight Intensive Observation Periods (IOPs) and three Limited Observation Periods (LOPs) were completed on rapidly intensifying storms and other relevant weather systems, e.g., comparison and inter-storm cases. A pre-ERICA test LOP was also completed on a rapidly-intensifying storm in January 1988. The occurrence of weather events suitable for ERICA research purposes was indeed fortunate; however it was also in close alignment with anticipations exhibited in planning reports, in particular the ERICA Field Operations Plan, taking into account the storm climatology data contained in the ERICA Storm Atlas. ERICA objectives and measurement plans were discussed in the Bulletin of the American Meteorological Society (Hadlock and Kreitzberg, 1988) and information presented in that article will largely not be repeated here. This report provides a synopsis of field study accomplishment and it briefly indicates the contents of the ERICA Field Phase Summary; observations are described to provide the general background for research papers and discussion on ERICA that follow in this symposium.

Figure 1 shows occurrence of 9 storms in the ERICA measurement region (from about 30 to 50 degrees North Latitude and 45 to 80 degrees West Longitude) during the ERICA season as heavy lines on a background of 108 historical storms during the 23 winter seasons 1965-66 through 1987-88. Straight lines (for convenience; therefore not storm tracks) are drawn for each storm, from the beginning to ending of pressure deepening at a rate of at least 10mb/6hr for at least 6 hr (ERICA-type storm). The data are taken unmodified, from the National Meteorological Center (NMC) three-hourly North American Surface Weather charts. Seven of the nine ERICA-type storms of winter 1988-1989 appear to have occurred south of most of the 108 historical storms, likely in dynamical association with the Gulf Stream;

see Kreitzberg and Cohen, 1990. By far most of the storm activity in the ERICA region occurred during the first 60 percent of the field study (Figure 2); following 21 January, only a single, and marginal, ERICA-type storm occurred (IOP 8, 23-26 February).

The IOPs and LOPs within which ERICA-type storms were observed and documented during winter 1988-89 are listed in Table 1. The pre-ERICA storm, of January 1988 (LOP 1P) and other weather events (LOPs 4A and 6P as well as IOPs 6 and 7 - without well-defined storm centers) are added to the list. The term "IOP" does not necessarily imply an ERICA-intensity storm, nor does "LOP" necessarily imply the absence of such. Two of the nine winter 1988-89 storms of ERICA intensity were not observed; the storm of 29-30 December, tracking to the north of Nova Scotia, and the storm of 3-4 January 1989 in the eastern measurement region was not observed in favor of the anticipated "monster" storm of IOP 4. Many other storms rapidly intensified during the ERICA field study, but so far to the east that they were beyond reasonable reach of the ERICA observational resources. The ERICA resources were fully expended, as planned, on an anticipated number of weather events, including comparison cases, e.g., IOPs 6 and 7.

2. Surface-based observations

Regular National Weather Service (NWS) and Atmospheric Environment Service (AES) soundings at 0000 and 1200UTC over the United States and Canada were supplemented by special soundings. About 700 extra soundings were taken at 6-hour and 3-hour intervals, between the regular soundings, at selected sites in the eastern United States and Canada. Table 2 shows the number of these supplementary soundings during each of the IOPs and LOPs and, for a small fraction of the total, between IOPs/LOPs. The latter were mainly in support of other ERICA-related measurements in Atlantic Canada and usually followed the official endings of observation periods by only a few hours. The table also indicates more than 500 CLASS (Cross-chain LORAN Atmospheric Sounding System) soundings from eight sites installed in Atlantic Canada and the northeast U.S. for the field study. Ordinarily, selected CLASS sites provided soundings at 3-hour intervals during the observation periods; again, a small fraction of the total soundings were taken in inter-IOP/LOP periods, usually following closely the official endings of observation periods.

About 1200 special supplementary and CLASS soundings were successfully completed during the field study. These soundings were augmented by sound-

ings from a Pennsylvania State University 404 Mhz pulsed Doppler profiler system located during the field phase at Otis Air Force Base on Cape Cod. The system operated continuously through most of the duration of IOPs/LOPs, starting during IOP 3. Special radars, complementing regular NWS and AES radars were operated, during near-shore weather-related intervals, at Halifax, Nova Scotia, Holyrood, Newfoundland, and at the Air Force Geophysical Laboratory, Sudbury, Massachusetts. Surface weather observations were obtained at the sounding sites, and with specialized research facilities at Halifax including precipitation physics equipment and a mesonet of observing stations.

Permanent NWS and AES moored buoys, and special moored buoys operated by AES and the Woods Hole Oceanographic Institution during the field phase, provided data at and near the ocean-atmosphere interface. Surface atmospheric pressure, and sea-surface and air temperature were additionally observed from aircraft-launched drifting buoys deployed over the ERICA measurement region. Ninety-one CMOD (Compact Meteorological and Oceanographic Drifter, METOCEAN Data Systems Limited) were employed to acquire, through satellite data link, data for production of hourly values of those quantities. The buoys were not configured to be good followers of ocean currents - rather, it was intended that the buoys were to remain in the ERICA measurement region and to transmit data for a reasonable duration, e.g., two weeks. Figure 3 shows successful lodging of ERICA drifting buoys in the central region of the storm of IOP 5; five buoys were launched during IOP 5, six just prior to the IOP, and three remained active from previous IOPs. Table 2 provides information of the deployments, during and between IOPs and LOPs, as well as the number of buoys that provided hourly data during the observing periods; drifting buoy data also exist, in large quantity, during inter-IOP/LOP periods. Weather at sea was further observed from commercial and Navy ships traveling through the ERICA region.

3. Aircraft-based observations

Eighty-seven research and reconnaissance aircraft missions were flown in support of ERICA, including activity during the pre-ERICA test (LOP 1P) of January 1988. Table 3 lists the IOP and LOP missions accomplished by the two NOAA Office of Aircraft Operations WP-3Ds, the NCAR Research Aviation Facility Electra and Sabreliner, the Naval Research Laboratory P-3 and several Air Force Air Weather Service WC-130s flying under the auspices of the National Winter Storms Operations Plan. The total of aircraft flight hours

was about 570. All of the WP-3D flights deployed LeSonde Loran-C dropwindsondes and all of the WC130 flights deployed Omega dropwindsondes, within IOPs and LOPs. The IWRS-equipped (Improved Weather Reconnaissance System) WC-130 was available only during IOPs 1 and 2, therefore Omegasonde winds were not available at other times. The Electra participated in the LeSonde activity on some flights, with missions during and between IOPs and LOPs (inter-IOP/LOP missions (4) and LeSondes (9) are shown in Table 3 by underlining); the NRL P-3 flew one mission with LeSonde releases during the field study, in IOP 3. Fifteen of the Sabreliner's high-altitude missions, for jet-stream and tropopause investigations, were conducted between IOPs and in support of ERICA's need for upper-level data.

Except for the Naval Research Laboratory's P-3, the aircraft were comprehensively equipped with instrumentation that acquired high resolution flight-level *in situ* data. The WP-3Ds acquired substantial radar data (utilizing 194 6250bpi magnetic tapes) during storm-related missions, including Doppler imagery from aircraft N42RF. The WP-3Ds additionally employed cloud physics observational systems which were operated at appropriate times during the missions. Many of the WP-3D flights incorporated rapid ascents and descents over altitude ranges in excess of 200 mb; ten megabytes of flight-level data from these episodes are organized into equivalent atmospheric soundings.

4. Satellite-based observations

The ERICA Satellite Atlas (June 1989) contains a subset of about 300 GOES (Geostationary Operational Environmental Satellite) images at 3-hourly intervals, of the approximately 1400 visible, infrared, and water vapor images obtained and archived for ERICA by the Satellite Applications Laboratory (SAL) of NESDIS (National Environmental Satellite, Data, and Information Service). Also included in the Atlas are the approximate 150 DMSP (Defense Meteorological Satellite Program) visible and infrared images obtained by the MacDill Air Force Base MARK IV satellite terminal system during and between ERICA observation periods. The Atlas serves as a guide in the initiation of research with the imagery and as a guide to procuring high-quality imagery from the ERICA Data Center.

5. Documents, data and the ERICA CD ROM

The ERICA Storm Atlas (7/87), Field Implementation Plan (11/87), Field Operations Plan (11/88), Field Phase Summary (5/89), Satellite Atlas

(6/89), Data Users' Guide (3/90), and data CD ROM (9/90) have been distributed to ERICA field participants and other interested persons. Copies of these ERICA documents, and the data - on CD ROM and otherwise, may be requested from the ERICA Data Center (OMNET address: ERICA.DATA.CENTER) at the Department of Physics and Atmospheric Science, Drexel University, Philadelphia, Pennsylvania 19104.

The data on the first ERICA compact disk (CD ROM, 9/90) are divided into 14 directories, listed below. Each data set is equipped with its own documentation and sample FORTRAN program, and additional documentation is provided on microfiche. Copies of the CD ROM are available for \$35 each.

P3FLD	Compressed P-3 Flight-Level Data, version 2
NCARFLD	Compressed NCAR Flight-Level Data, version 2
OTHERAC	PIREPS from PROFS, ACARS, version 2
SND2	Master Sounding Files, version 2
SST14	14 Km ASCII SST Files, version 2
SST50	50 Km ASCII SST Files, version 2
EDC3280	EDC Reformatted NCDC Surface Hourly Airways, version 4
DATSAV	EDC Reformatted DATSAV Surface Data, version 2
CANHLY	EDC Reformatted Canadian Surface Hourly, version 1
MESONET	EDC Reformatted Nova Scotia Mesonet Data, version 1
SHIP	EDC Combined TD-1129 Format Ship Data, version 5
BUOY	EDC Combined Buoy and C-MAN Data, version 1
DOC	CD ROM Documentation, including the ERICA Data Users' Guide
GEOG	North American Detailed Elevation and Land Use Data

6. References

Hadlock, R. and C.W. Kreitzberg, 1988: The experiment on rapidly intensifying cyclones over the Atlantic (ERICA) field study: objectives and plans. *Bull. Amer. Meteor. Soc.*, 69, 1309-1320.

Kreitzberg, C.W., and R.A. Cohen, 1990: The role of atmospheric and sea-surface temperature fronts near the Gulf Stream in ERICA. Extended Abstracts, Fourth Conference on Mesoscale Processes, American Meteorological Society, Boston.

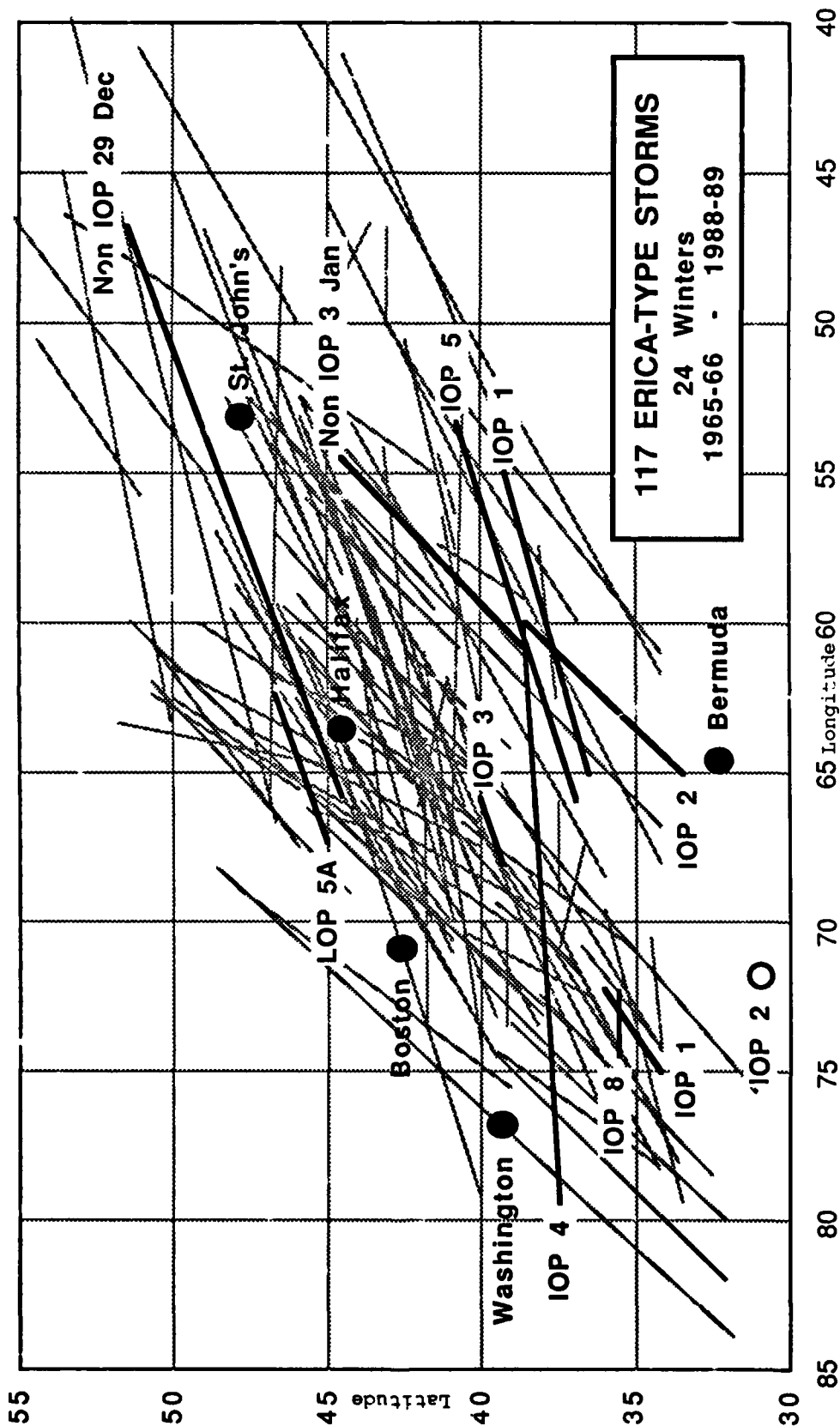


Fig. 1. Straight lines are drawn from beginning to ending of rapid intensification (at least 10mb/6hr for at least 6 hr) for 117 ERICA-type storms over twenty four winter seasons. The heavier lines represent the nine ERICA-type storms that occurred in and near the measurement region during the field study. The circle at 31N, 72W indicates a stationary (first of two) rapid intensification during IOP 2. This diagram utilizes only NMC North American chart data for the historical storms.

Table 1. ERICA intensive and limited observation periods

IOP/LOP Number	IOP/LOP Beginning and Ending Times, and Duration (hr)	Minimum Pressure (mb)	Maximum 6-hr drop (mb)	Rapid Intensification(s) and Duration(s) (_mb/_hr)
LOP1P	Jan 26 1988 0000UTC	N966	N14	N14/6, 11/6
	Jan 26 2100UTC, 21.0	E964	E11	E21/12
IOP 1	Dec 9 1988 1200UTC	N980	N14	N14/3, 18/9
	Dec 10 1930UTC, 31.5	E985	E10	E10/6, 14/9
IOP 2	Dec 12 1988 1500UTC	N962	N15	N10/6, 29/12
	Dec 15 0000UTC, 57.0	E960	E18	E9/6,39/18
IOP 3	Dec 17 1988 0000UTC	N974	N10	N10/6
	Dec 19 0000UTC, 48.0	E978	E10	E10/6
----	Dec 29-30 1988	N946	N15	N33/18
	(not observed by ERICA)			
----	Jan 3-4 1989	N964	N18	N30/18
	(not observed by ERICA)			
IOP 4	Jan 3 1989 1200UTC	N940	N27	N16/6, 45/12
	Jan 6 1200UTC, 72.0	E938	E24	E13/6, 37/12
LOP4A	Jan 11 1989 1200UTC	----	----	----
	Jan 14 0000UTC, 60.0			
	(interstorm)			
IOP 5	Jan 18 1989 1800UTC	N965	N16	N22/9, 14/6
	Jan 20 1200UTC, 42.0	E969	E18	E33/15
LOP 5A	Jan 20 1989 1200UTC	N964	N15	N25/12
	Jan 21 1800UTC, 30.0	E964	E15	E28/15
LOP6P	Jan 27 1989 1500UTC	----	----	----
	Jan 28 0600UTC, 15.0			
	(weak low centers)			
IOP 6	Feb 8 1989 0800UTC	----	----	----
	Feb 9 0100UTC, 17.0			
	(no closed low)			
IOP 7	Feb 12 1989 0600UTC	----	----	----
	Feb 13 1200UTC, 30.0			
	(no closed low)			
IOP 8	Feb 23 1989 2000UTC	N986	N9	N9/6
	Feb 26 0600UTC, 58.0	E984	E9	E9/6

E - data from ERICA analyses, N - data from NMC analyses, UTC - Universal Time Convention

Table 2. Numbers of special soundings and drifting buoys during and between ERICA IOPs and LOPs

1P	1	2	3	4	4A	5	5A	6P	6	7	8	Total					
U.S. and Canadian supplementary rawinsondes:																	
--	37	<u>1</u>	86	<u>2</u>	86	120	10	82	21	35	9	<u>6</u>	67	<u>10</u>	102	<u>10</u>	684
U.S. and Canadian CLASS rawinsondes:																	
--	24	31	<u>4</u>	54	96	36	56	38	<u>5</u>	25	5	<u>8</u>	59	<u>6</u>	62		509
Drifting buoys deployed:																	
--	<u>30</u>	16	1	8	3	2	<u>6</u>	5	0	2	<u>7</u>	3	<u>1</u>	1	6		91
Drifting buoys that provided hourly data during IOPs/LOPs:																	
--	41	39	39	5	5	14	13	7	15	16	18						--

underlining indicates launches between IOPs/LOPs.

underlining indicates launches between IOPs/LOPs.

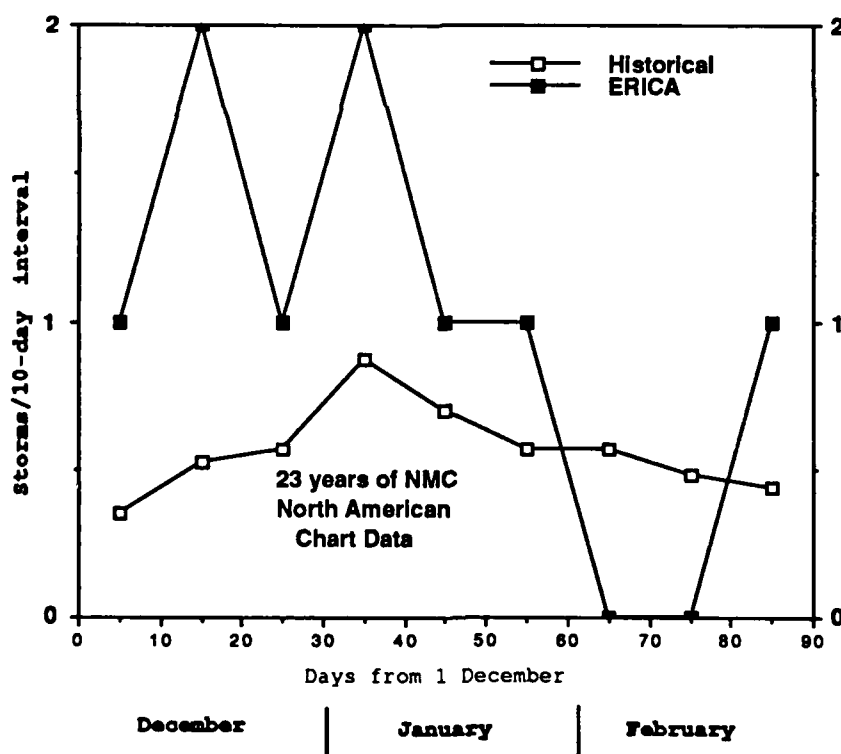


Fig. 2. Distribution of ERICA-type historical and field phase storms in 10-day intervals from 1 December through 28 (29) February. The historical storm occurrence data are divided by 23 years, the period for which the historical NMC data were considered. The number of ERICA field phase storms was larger than expected and they occurred in the first two months with the exception of the storm of IOP8 which was marginal at 9mb/6hr.

Table 3. Number of aircraft flights and (dropsondes) during and between
ERICA IOPs and LOPs

Aircraft												
1P	1	2	3	4	5	5A	6P	6	7	8	Total	
WP-3Ds												
2(6)	1(14)	3(22)	2(24)	2(9)	2(27)	1(15)	---	---	2(33)	---	15(144)	
(ERICA1)												
---	1(13)	---	2(15)	3(57)	2(9)	---	1(38)	1(8)	1(10)	2(27)	13(177)	
(ERICA2)												
---	1	1(5)	---	1	1(4)	1(6)	1(11)	---	---	---	6(26)	
(ERICA3)												
---	1	1	---	1*	2(9)	2	1	1	1	---	4(9)	
Sabreliner												
---				2	5	2	6				15	
(ERICA4)												
---	---	---	1(5)	---	---	---	---	---	---	---	1(5)	
NRL P-3												
(ERICA5)												
3(18)	3(6)	5(31)	3(20)	3(22)	2(16)	1(7)	---	2(7)	1(7)	1(8)	24(142)	
WC-130s												
(with IWRS)												
(14)												
(8)												
(22)												
Total flights												
5	7	10	8	3	9	7	9	5	2	4	3	8
Total sondes												
24	47	66	60	88	2	56	28	49	15	50	35	531

* underlining indicates launches between IOPs/LOPs

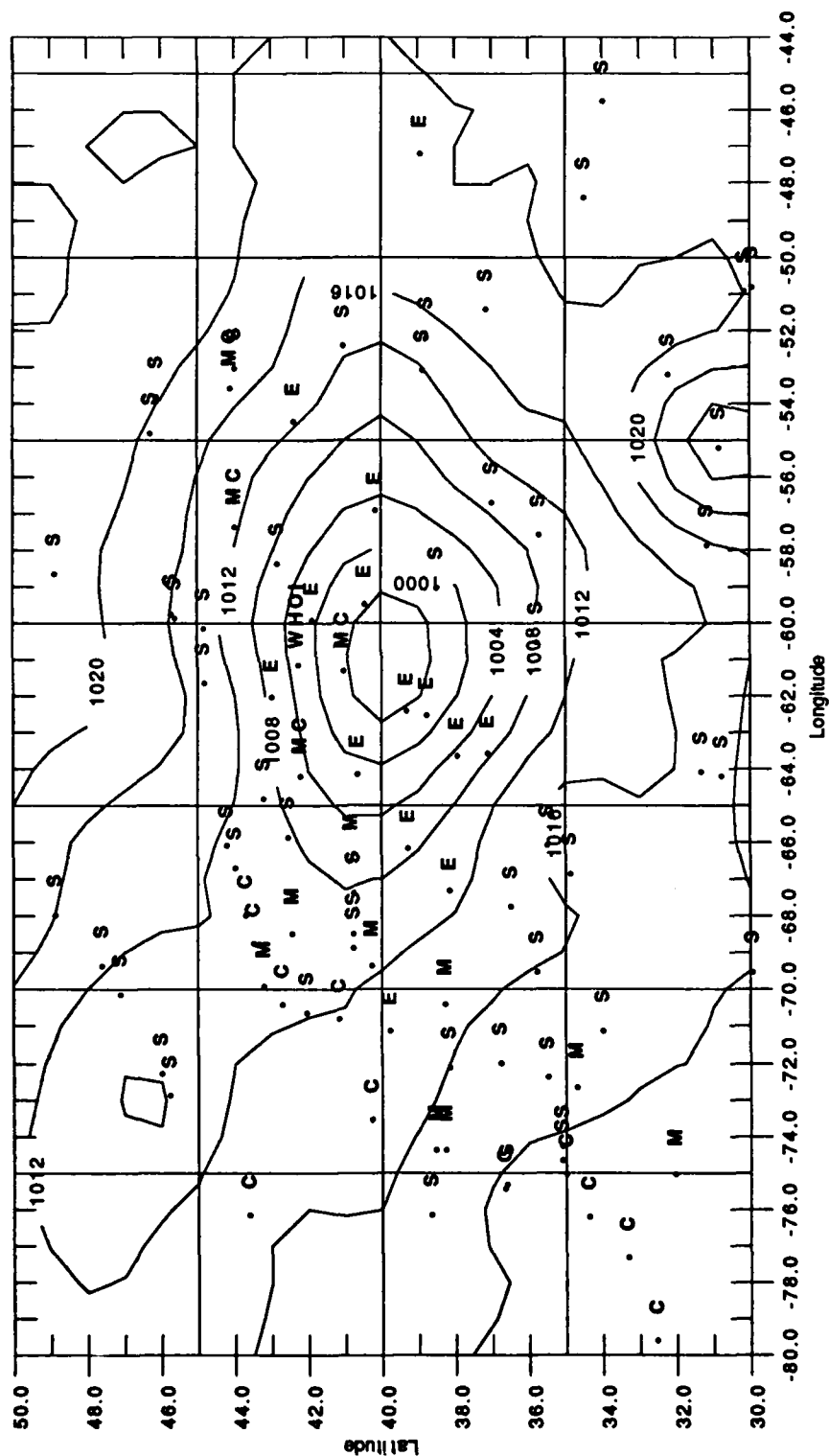


Fig. 3. Surface data reporting stations for 19 January 1989, 18 UTC during IOP5. Preseeding of the region with drifting buoys, and those remaining from prior IOPs produce substantial pressure data coverage in the central region of the storm, inside the 1008 mb isobar. The isobars are obtained through a computer process of univariate analysis on the pressure data for the larger region shown. S = ship, E = drifting buoy, C = C-MAN, WHOI = Woods Hole moored buoy, M = U.S. moored buoy, MC = Canadian moored buoy.